

Miniature Loop Heat Pipe with Multiple Evaporators for Small Spacecraft Thermal Control

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Abstract: *This paper presents the development of the Thermal Loop experiment under NASA's New Millennium Program Space Technology 8 (ST8) Project. The Thermal Loop experiment will validate in space an advanced heat transport system consisting of a miniature loop heat pipe (MLHP) with multiple evaporators and multiple condensers. The purpose of the flight experiment is to advance the maturity of the MLHP technology from "proof of concept" to "demonstration in space", i.e. from a technology readiness level (TRL) of 3 to a level of 7. Details of the thermal loop concept, technical advances and benefits, level 1 requirements and the technical approach are described. An MLHP breadboard has been built and tested in the laboratory and thermal vacuum environments for TRL 4 and 5 validation. The MLHP demonstrated excellent performance that met or exceeded the requirements. The MLHP retains all features of state-of-the-art LHPs and offers additional advantages to enhance the functionality, performance, versatility, and reliability of the system. In addition, an analytical model has been developed to simulate the steady state and transient operation of the MLHP, and the model predictions agreed very well with experimental results in the laboratory and thermal vacuum testing. A protoflight MLHP for TRL 6 and 7 validation is being built.*

Keywords: two-phase heat transfer, spacecraft thermal control; miniature loop heat pipe

Introduction

A loop heat pipe (LHP) is a very versatile heat transfer device which can transport a large amount of heat over a long distance with a small temperature difference [1, 2]. LHPs have been used for thermal control of many commercial communications satellites and NASA's spacecraft, including ICESAT, AURA, SWIFT, and GOES [3-5]. All LHPs currently servicing orbiting spacecraft have a single evaporator with a 25-mm outer diameter primary wick. When the heat source has a large thermal footprint, or several heat sources need to be controlled at similar temperatures, an LHP with multiple evaporators is highly desirable. For small spacecraft applications, miniaturization of the LHP is necessary in order to meet the stringent requirements of low mass, low power and compactness. Also important in the thermal subsystem development are the need for design flexibility which allows for optimum placement of components. Under

NASA's New Millennium Program Space Technology 8 (ST8) Project, the Thermal Loop experiment will validate in space the performance of a miniature loop heat pipe (MLHP) with multiple evaporators and multiple condensers. Each evaporator has a primary wick with an outer diameter of 6.35 mm.

The ST8 project comprises four experiments: Thermal Loop, Dependable Microprocessor, SAILMAST, and UltraFlex. The purpose of the ST8 project is to advance the maturity of the four technologies from "proof of concept" to "demonstration in space", i.e. from a technology readiness level (TRL) of 3 to a level of 7. For the Thermal Loop experiment, an LHP Breadboard has been built and tested in the laboratory and thermal vacuum environments for TRL 4 and 5 validation. The LHP Breadboard demonstrated excellent performance that met or exceeded all requirements. In addition, an analytical model has been developed to simulate the steady state and transient operation of LHPs, and model predictions agreed very well with experimental results in the laboratory and thermal vacuum testing of the LHP Breadboard. A protoflight LHP to be used for TRL 6 and 7 validation is being built.

This paper presents the Thermal Loop concept, technical advances and benefits, experiment objectives, Level 1 requirements, and the technical approach for technology validation. In particular, the LHP Breadboard testing and the analytical model predictions that validated the attainment of TRL 5 of the Thermal Loop technology will be described. Also addressed are the development of the protoflight unit and the flight operations concept for TRL 7 validation.

Thermal Loop Concept

Figure 1 shows the Thermal Loop experiment concept. At the heart of the Thermal Loop experiment is an MLHP which transports heat loads from the heat sources to the heat sinks while maintaining tight temperature control for all instruments under varying heat load and environmental conditions.

Key features of the Thermal Loop experiment include: 1) Multiple evaporators in a single LHP where each evaporator has its own integral compensation chamber (CC); 2) Each evaporator has a primary wick with an outer diameter (O.D.) of 6.35mm; 3) Multiple condensers that are attached to different radiators; 4) A thermoelectric converter (TEC) that is attached to each CC and connected

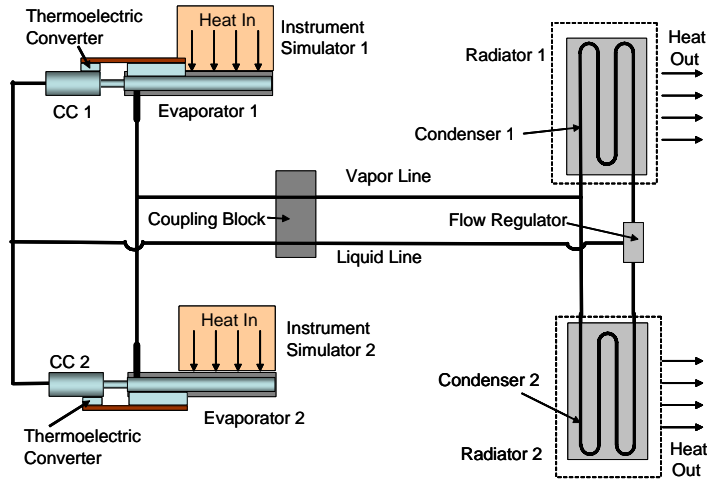


Figure 1. Thermal Loop Experiment Concept

to the evaporator via a thermal strap; 5) A flow regulator located downstream of the condensers; 6) Coupling blocks connecting the vapor line and liquid line; and 7) ammonia working fluid.

Technical Advances and Benefits

Table 1 summarizes the technical advances and benefits of the Thermal Loop technology. Most comparisons are made in reference to state-of-the-art single-evaporator LHPs. Details are described below.

Multiple Miniature Evaporators: An LHP utilizes boiling and condensation of the working fluid to transfer heat, and surface tension forces developed by the evaporator wick to circulate the fluid [1-2]. This process is passive and self-regulating in that the evaporator will draw as much liquid as necessary to be completely converted to vapor according to the applied heat load. When multiple evaporators are placed in parallel in a single loop, each evaporator will still work passively. No control valves are needed to distribute

the fluid flows among the evaporators. All evaporators will produce vapor that has the same temperature as liquid vaporizes inside individual evaporators regardless of their heat loads. The loop works as a thermal bus that provides a single interface temperature for all instruments, and the instruments can be placed at their optimum locations. Furthermore, the instruments that are turned off can draw heat from the instruments that are operational because the evaporators will automatically share heat among themselves [2, 6]. This will eliminate the need for supplemental electrical heaters while maintaining all instruments close to the loop operating temperature. The heat load sharing function among evaporators is passive and automatic. Therefore, each instrument can operate independently without affecting other instruments. When all instruments are turned off, the loop can be shut down by keeping the CC at a temperature above the minimum allowable instrument temperature. No heat will flow to the condensers/radiators. Thus, the loop works as a thermal switch.

Table 1. Technical Advances and Benefits of Thermal Loop Technology

State-of-the-Art	ST8 Technical Advance
LHP has a single evaporator	LHP has multiple evaporators (Thermal Loop will have two evaporators for demonstration)
Requires supplemental heaters to maintain temperatures of off-instruments	Heat load sharing among evaporators eliminates or reduces supplemental heater powers
LHP has 25mm wick	LHP has 6.35mm wick - reduced volume and mass
Top-level transient model for LHPs with a single evaporator	Detailed transient model for LHPs with multiple evaporators
No scaling rule has been established	Scaling rules will be established
Relies on starter heater on evaporator for start-up Power required: 20W to 40W	Uses TECs on CCs to ensure successful start-up Power required: less than 5W
Control heater on CC for temperature control - cold biased, heating only, no cooling, Heater power: 5W to 20W	TECs on CCs and coupling block on transport lines for temperature control - heating and cooling Heater power: 0.5W to 5W

The primary wick in the evaporator has an outer diameter of 6.35mm. The evaporator mass is therefore reduced by more than 70 percent when compared to the evaporator having a 25mm O.D. primary wick used in state-of-the-art LHPs. Small evaporators also reduce the required fluid inventory in the LHP, and the mass and volume of the thermal system.

Multiple Condensers/Flow Regulator: The fluid flow distribution among multiple, parallel condensers is also passive and self regulating [2, 6]. Each condenser will receive an appropriate mass flow rate so that the conservation laws of mass, momentum and energy are satisfied in the condenser section. If a condenser is fully utilized, such as when the attached radiator is exposed to a warm environment, vapor will be prevented from leaving that condenser by the capillary flow regulator located downstream of the condensers, and any excess vapor flow will be diverted to other condensers. Thus, no heat will be transmitted from a hot radiator back to the instruments, effecting a thermal diode action.

TECs: The LHP operating temperature is governed by its CC temperature. The CC temperature as a function of the evaporator power at a given condenser sink temperature follows the well-known V-shaped curve as shown in Figure 2. The resulting temperature curve is the LHP natural operating temperature. The CC temperature can be controlled at a desired set point temperature of T_{set} . The state-of-the-art approach is to cold bias the CC and use electrical heaters to raise the CC temperature. As shown in Figure 2, the CC temperature can be controlled at T_{set} between heat loads of Q_{Low} and Q_{High} . However, this technique does not work for $Q < Q_{Low}$ where the natural operating temperature is higher than the desired set point temperature. The CC requires cooling instead in order to maintain its temperature at T_{set} .

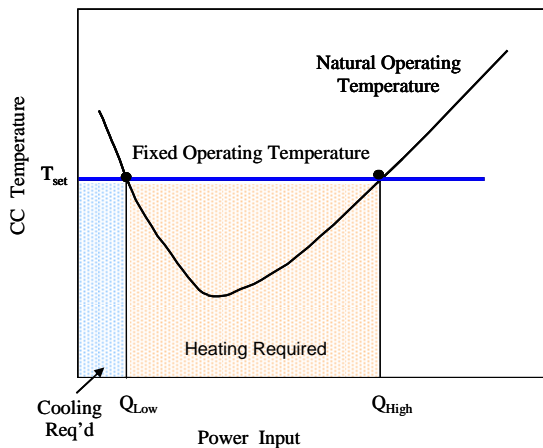


Figure 2. LHP Operating Temperature

A TEC can be attached to the CC to provide heating as well as cooling to control the CC temperature. One side of a TEC can be attached to the CC, while the other side can be

connected to the evaporator through a flexible thermal strap. When the TEC is cooling the CC, the total heat output from the TEC hot side, i.e. the sum of the power applied to the TEC and the heat pumped out of the CC, is transmitted to the evaporator and ultimately dissipated to the condenser. When the TEC is heating the CC, some heat will be drawn from the evaporator through the thermal strap to the TEC cold side. The sum of the power applied to the TEC and the heat drawn from the evaporator is delivered to the CC. The heat drawn from the evaporator reduces the power required to heat the CC. The power savings derived from using a TEC can be substantial when compared to conventional electric heaters, especially when the evaporator has a high/medium heat load and the condenser is exposed to a very cold environment.

The operating temperature of the MLHP can be maintained by controlling any number of CC's at the desired set point temperature [7]. Control can also be switched from one CC to another at any time. Furthermore, the CC set point temperature can be changed upon command while the loop is operational. The ability of the CC to control the loop operating temperature at a constant value makes the MLHP function as a variable conductance thermal device.

In addition to maintaining the CC temperature, the TECs can be used to enhance the LHP start-up success. A typical LHP start-up involves raising the CC temperature above the evaporator temperature and then applying power to the evaporator. As the evaporator temperature rises above the CC temperature by a certain amount (the superheat), vapor bubbles will be generated in the evaporator and the loop will start, as shown in Figure 3(a). However, the required superheat for boiling is stochastic and can range from less than 1K to more than 10K. A high superheat can lead to start-up difficulty because, while the evaporator temperature is rising to reach the required superheat, the CC temperature also rises due to the heat leak from the evaporator. Thus, the required superheat for bubble generation may never be attained, as shown in Figure 3(b). This is especially true when a low heat load is applied to the evaporator and a high superheat is required. The net heat load to the evaporator will be small during the start-up transient when the evaporator is attached to an instrument. To overcome the start-up difficulty, the state-of-the-art LHPs use a small-sized starter heater to provide a highly concentrated heat flux to generate first vapor bubbles locally. The required starter heater power is on the order of 30W to 60W for standard LHPs with a 25mm O.D. evaporator. For LHPs with small evaporators, the required starter heater power is estimated to be between 20W and 40W.

The TEC attached to the CC can maintain a constant CC temperature, and ensure that the evaporator will eventually overcome the required superheat no matter how high the required superheat and how low the heat load are, i.e. the condition shown in Figure 3(a) will occur. Alternatively,

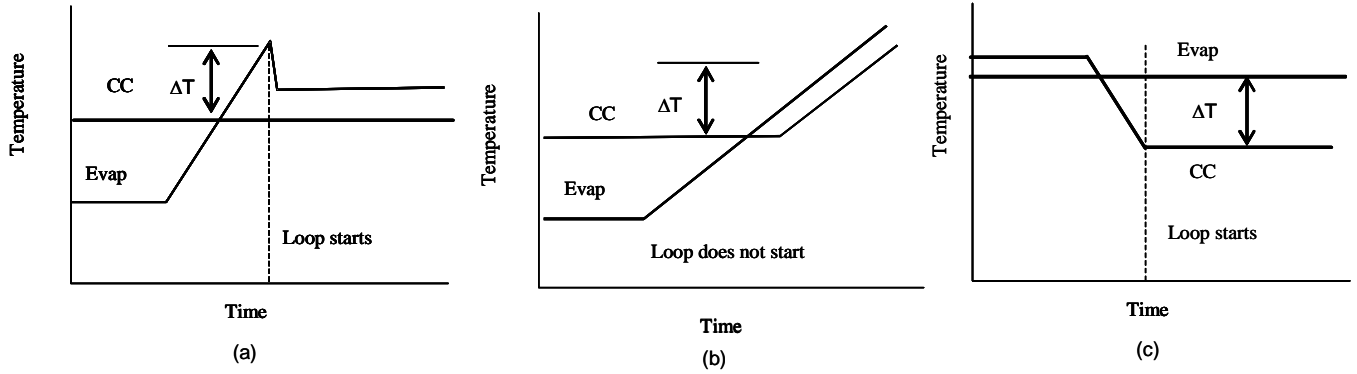


Figure 3. LHP Start-up

the TEC can be used to lower the CC temperature during the start-up transient to achieve the required superheat as shown in Figure 3(c). Regardless of which method is implemented, the required starter heater power can be reduced or eliminated.

Coupling Block: The coupling block allows the liquid returning to the evaporator/CC to absorb heat from the vapor line, which further reduces the control heater power when TEC is heating the CC.

Analytical Models and Scaling Criteria: Part of the technology development for the Thermal Loop experiment is to develop an analytical model which simulates the steady state and transient behaviors of LHPs. The analytical model is based on conservation laws governing the operation of an LHP with multiple evaporators and multiple condensers. The model solves a set of differential equations using Lagrangian method. Inputs to the model include detailed geometries of the LHP components, the evaporator power profile, and environmental conditions. Outputs of the model are temperature and pressure distributions in the LHP. The model can be used as a stand-alone model for LHP design analysis, or as a subroutine for a general spacecraft thermal analyzer such as SINDA/Fluint [8]. The MLHP experimental data in laboratory, thermal vacuum, and space flight tests will be correlated with the model predictions to validate the attainment of various TRLs during the course of the Thermal Loop technology development.

The LHP operation involves some very complicated fluid and thermal processes, which are strongly influenced by gravitational, inertial, viscous, and capillary forces. To obtain better understanding of fluid flow and heat transfer phenomena in an LHP and to provide a means of comparison and generalization of data between different LHPs, some scaling criteria are needed. In addition to the LHP analytical model, a set of dimensional and dimensionless groups has been developed to relate geometry and configuration of the LHP components,

properties of the wick and the working fluid, and the environmental conditions surrounding the LHP [9].

Performance Characteristics: Figure 4 illustrates the performance of an MLHP having two evaporators and two condensers. The loop can be started by raising the CC temperature at a desired temperature that is above the ambient temperature using the TECs so as to flood the evaporators with liquid, and then turning on the instruments. Because the TECs can keep the CC temperature constant, the loop will start. The heat loads to the evaporators can vary independently; both evaporators will yield 100 percent vapor at the same temperature. The two condensers will dissipate the total heat load coming

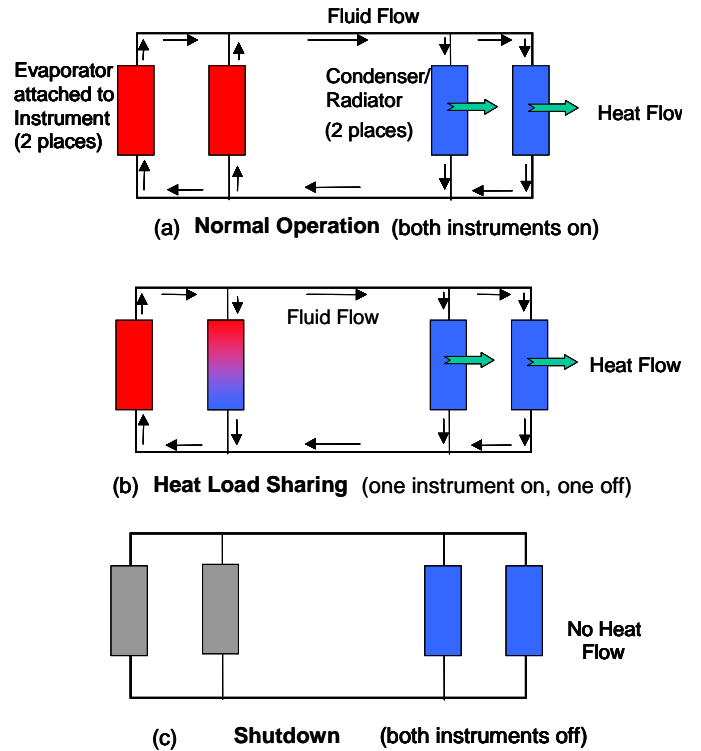


Figure 4. MLHP Operating Modes

from the evaporators. The load will be automatically distributed between two condensers according to the conservation laws. When an instrument is turned off, part of the heat load from the “on” instrument will flow to the “off” instrument. When both instruments are turned off, the loop can be shut down as long as the CC temperature is maintained above the minimum allowable instrument temperature, and no heat will be transmitted from the instruments to the radiators.

Experiment Objectives and Level 1 Requirements

The objective of the Thermal Loop experiment is summarized below:

- Verify zero-g performance of an MLHP with multiple evaporators and multiple condensers, and heat load sharing among evaporators in particular. Identify and understand performance differences between one-g and zero-g environments, if any.
- Verify that the MLHP can start reliably and repeatedly in zero-G. Identify and understand differences in start-up transients between one-g and zero-g environments, if any.
- Verify that LHPs with 6.35 mm OD wicks function in a similar manner as those with 25 mm OD. Identify and understand performance deviations, if any.
- Verify feasibility of using TECs for LHP startup and operating temperature control. Verify that any or all of the CCs can be used for temperature control, and that control can be switched from one CC to another.
- Verify that use of TECs leads to a significant reduction in auxiliary heater power for LHP startup and operating temperature control.
- Verify the ability of the MLHP analytical model to predicting transient behaviors in zero-g space environment.

Table 2 summarized the Thermal Loop experiment Level 1 requirements and full and minimum success criteria.

Technology Validation Approach

The purpose of the ST8 project is advance the maturity of the four technologies from “proof of concept” to “demonstration in space”, i.e. from a technology readiness level (TRL) of 3 to a level of 7. The requirements for the attainment of technology maturity at various project phases are: 1) TRL 4 at the end of Phase A, 2) TRL 5 at the end of Phase B, 3) TRL 6 at the end of Phase D, and 4) TRL 7 at the end of Phase E. In response, the technical approach taken by the Thermal Loop experiment for technology validation is as follows:

- Test the LHP Breadboard in a laboratory environment to validate TRL 4
- Test LHP Breadboard in a thermal vacuum chamber to validate TRL 5
- Fabricate an LHP flight unit. Test the flight unit in a thermal vacuum to validate TRL 6 and in space to validate TRL 7
- Develop an analytical model to predict the behaviors of the MLHP Breadboard and protoflight unit in laboratory, thermal vacuum, and space flight tests at various TRLs

TRL 4 and TRL 5 Validation

An LHP Breadboard has been built and tested in laboratory and thermal vacuum environments. The loop demonstrated excellent performance and the Thermal Loop experiment has successfully demonstrated the attainment of TRL 4 and TRL 5. Details of the LHP Breadboard and the thermal vacuum testing will be described below.

Figure 5 shows a picture of the LHP Breadboard. Major design parameters are summarized in Table 3. The LHP Breadboard consisted of two parallel evaporators, two parallel condensers, a common vapor transport line and a common liquid return line. A thermal mass of 400 grams of aluminum was attached to each evaporator to simulate the instrument mass. The two parallel condensers were sandwiched between two aluminum plates. A flow regulator consisting of capillary wicks was installed at the

Table 2. Level 1 Requirements and Success Criteria

Baseline Technology Validation/Measurement Requirement	Full Project Success Criteria/Measurement Requirement	Minimum Project Success Criteria/Measurement Requirement
<ul style="list-style-type: none"> • Operate in space a miniature, multi-evaporator loop heat pipe for small system applications capable of an 80% success rate on a minimum of 20 start-ups. • Develop an analytical model which can predict the loop’s critical temperatures during steady state and transient operation. 	<ul style="list-style-type: none"> • Heat load-share two loads in the range of 0 to 75 W while the loads either remove or add heat to the system 	<ul style="list-style-type: none"> • Heat load-share two loads in the range of 0 to 50 W while the loads either remove or add heat to the system
	<ul style="list-style-type: none"> • Operating temperature of the Loop measured at the compensation chamber shall be within ± 3 K of the desired set point temperature over 273K to 308K range 	<ul style="list-style-type: none"> • Operating temperature of the Loop measured at the compensation chamber shall be within ± 5K of the desired set point temperature over 273K to 308K°C range

downstream of the two condensers. The vapor line and liquid line were connected with several aluminum coupling blocks (20 mm by 20mm by 6mm each). A TEC was installed on each CC through an aluminum saddle. The other side of the TEC was connected to the evaporator through a copper thermal strap. A close-up view of the evaporator/CC section showing the TECs and thermal straps is depicted in Figure 6. A cartridge heater capable of delivering 1W to 200W was inserted into each thermal mass. Each TEC was controlled by a bi-polar power supply. Changing the polarity of the power supply changed the TEC operation between the heating and cooling modes.

Table 3. Summary of MLHP Design Parameters

Component	Material	Value
Evaporators (2)	Aluminum 6061	9 mm O.D. x 52 mm L
Primary Wicks (2)	Titanium	6.35 mm O.D. x 3.2mm I.D. Porosity: 0.35 Pore radius 1.39 μm (E1), 1.47 μm (E2) Permeability: $0.11 \times 10^{-13} \text{m}^2$ (E1), $0.09 \times 10^{-13} \text{m}^2$ (E2)
Secondary Wicks (2)	Stainless Steel	Porosity: 0.67 Pore radius: 68.7 μm Permeability: $83 \times 10^{-13} \text{m}^2$
Bayonet Tubes (2)	SS 304L	1.1 mm O.D. x 0.79 mm I.D.
CC (2)	SS 304L	22.2 mm O.D. x 21.2 mm I.D. x 72.4 mm L
Vapor Line	SS 304L	2.38 mm O.D. x 1.37 mm I.D. x 914 mm L
Liquid Line	SS 304L	1.59 mm O.D. x 1.08 mm I.D. x 914 mm L
Condensers (2)	SS 304L	2.38 mm O.D. x 1.37 mm I.D. x 2540 mm L
Flow Regulator	SS	Pore radius: 10.1 μm Permeability: $3.1 \times 10^{-13} \text{m}^2$
Working fluid	Ammonia	29.3 grams
Total LHP mass		316.6 grams

For the thermal vacuum test, each condenser plate was exposed to a cryopanel which provided radiative cooling. To facilitate the heat load sharing test, a copper plate was attached to each evaporator thermal mass, and a coolant flow through the thermal mass provided the necessary heat sink. A chiller, located outside the thermal vacuum chamber, was used to circulate the coolant, and two valves were used to direct the flow to the intended thermal mass.

More than 120 type T thermocouples were used to monitor the MLHP and the radiator temperatures, as shown in Figure 7. Several thermocouples other than those shown in

Figure 7 were added to the radiators and the cryopanel. A data acquisition system consisting of a data logger, a personal computer, and a screen monitor was used to collect and store temperature and power data every second. Labview software was used for the command and control of the test conditions.

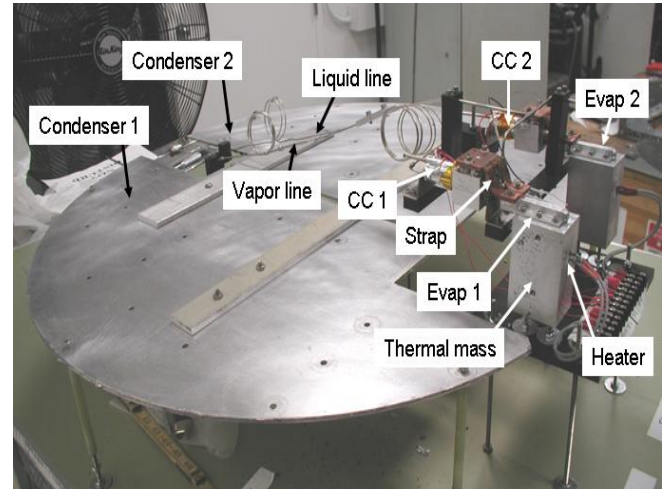


Figure 5. Picture of the MLHP

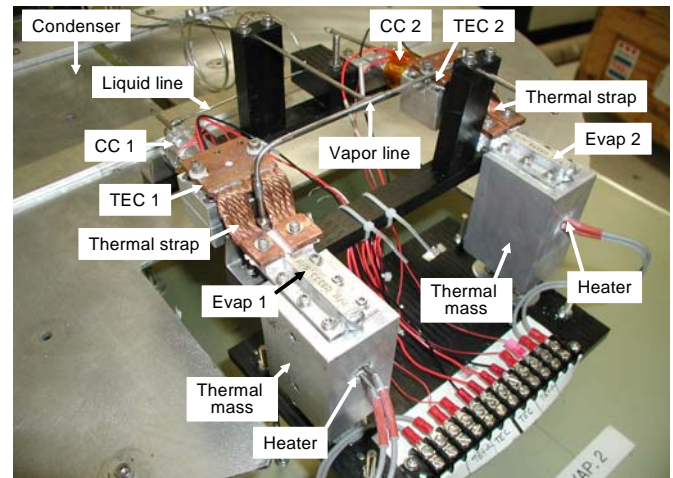


Figure 6. Close-up View of the Evaporator/CC Section

The LHP was tested in the laboratory and in a vacuum chamber, and yielded more than 1200 hours and 500 hours of test data, respectively. Performance of the LHP Breadboard met or exceeded the level 1 requirements. In addition, the LHP analytical model was developed, and the model predictions agreed very well with the experimental data. The Thermal Loop experiment has hence attained a TRL of 5. The experimental results were described in detailed in a technology validation reports and in several papers [10-14]. Some experimental results of the thermal vacuum test are highlighted below.

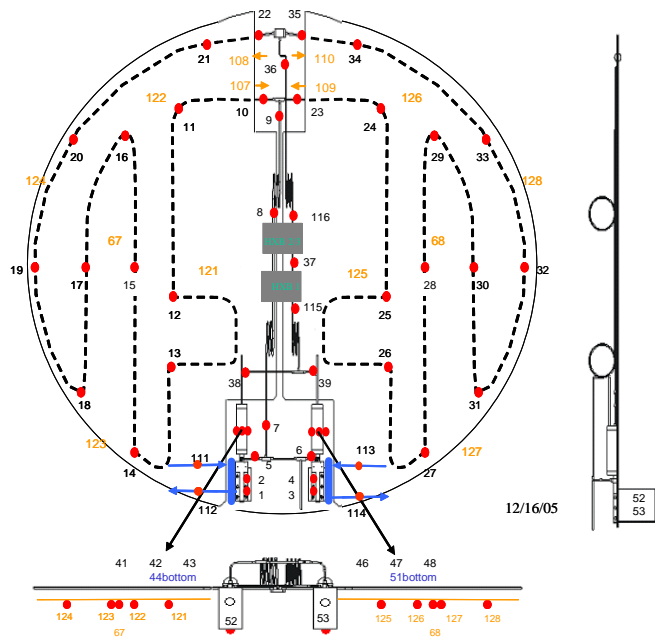


Figure 7. Thermocouple Locations

A problem was encountered during thermal vacuum testing. For some unknown reasons, sporadic data drops occurred. At every event of the data drop, all temperatures read 282K for a single data scan. In response to the erroneous CC temperature reading, the TECs would either cool or heat the CC in an attempt to bring the CC temperature to the desired set point. As a result, the CC temperature fluctuated about $\pm 1\text{K}$ for a few minutes until stable temperatures were reestablished. In the following descriptions of test results, the effect of such data drop can be clearly seen. For clarity, the single point of data drop was eliminated in all plots. Furthermore, in all plots, numbers in the parentheses denote the thermocouple locations shown in Figure 7.

Figure 8 shows a start-up test where a heat load of 50W/5W was applied to E1/E2 and the CC2 temperature was controlled at 293K. Prior to start-up, the entire loop except CC2 was completely flooded with liquid. When a heat load of 50W/5W was applied, E1 rose faster in temperature than E2. At the onset of nucleate boiling, E1 had a superheat of 7K. After vapor was generated in E1, E2 temperature rose much more quickly as it shared heat from E1. The successful start-up was followed by a power swap from 50W/5W to 5W/50W. As the loop continued to operate, CC1 temperature gradually rose to 293K although no control heater power was applied. This was a result of E1 sharing heat from E2, leading to a flow reversal in E1 [6].

Figure 9 shows the experimental data and the analytical model predictions for a start-up. Prior to applying a heat load to E1, CC1 was heated to 303K using TEC1. Pre-

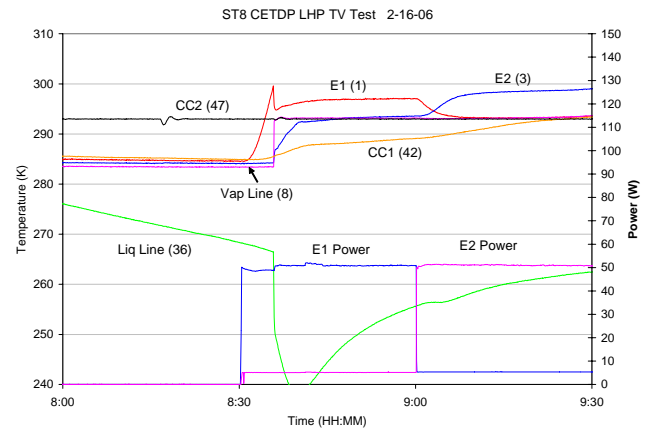


Figure 8. Loop Temperatures for 50W/5W Start-up

heating CC1 caused the E1 temperature to drop, indicating that E1 was flooded with liquid. With a heat load of 5W, E1 had a superheat of 1K at the onset of start-up. Note that before the loop started, the E2 temperature remained unchanged. Once the loop started and vapor was generated, E2 drew heat from E1 by way of heat load sharing and its temperature rose toward the CC1 saturation temperature. For the model prediction, the experimental data of 1K superheat at the onset of start-up was used as an input parameter. In general, the model predictions agreed very well with test results. The model also predicted correctly how vapor flowed preferentially to various components during the start-up transient. There was a shift of time in both figures between the predictions and the experimental data on the moment when E2 reached the saturation temperature and when the liquid line temperature began to drop after the loop started. These discrepancies were caused by the inaccuracy of the model predictions on how much heat was shared during the start-up transient. With a total heat load of only 5W into E1, the amount of heat that could be shared by E2 was very small. Any inaccuracy in

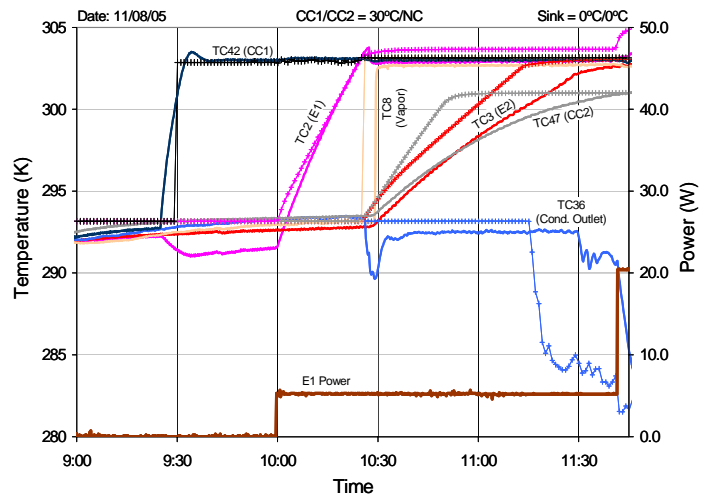


Figure 9. Analytical Model Predictions and Experimental Data for Start-up

the model prediction on the heat sharing would result in the inaccuracy of the time it took for E2 to reach the saturation temperature. This was particularly true given that a thermal mass of 400 gram aluminum was attached to each evaporator.

Figure 10 shows the temperatures for a power cycle test where the heat load to E1/E2 was varied as follows: 75W/0W, 50W/25W, 25W/50W, 0W/75W, 5W/50W, and 50W/5W. Both cryopanel were maintained at 173K, and both CCs were controlled at 293K using TECs. The TECs were able to keep both CCs at 293K at all times. The temperatures of E1 and E2 varied with the heat load as expected.

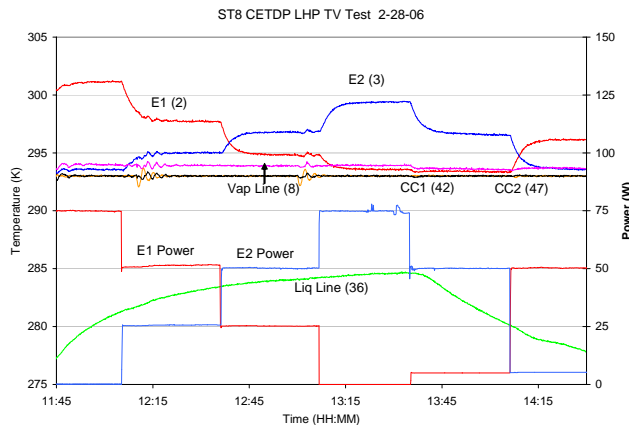


Figure 10. Uneven Power to E1 and E2

Figure 11 shows the loop temperatures in a high power test. Both CCs were controlled at 308K using TECs. The heat load to E1/E2 was 10W/10W, and then went up to 60W/60W with 10W/10W increments. The loop demonstrated a heat transport capability of 120W. The TECs controlled the CC temperatures within $\pm 0.5K$ at all times except for the periods following data drops where the CC temperature fluctuated $\pm 1K$ for a short duration before TECs resumed tight control of the CC temperatures.

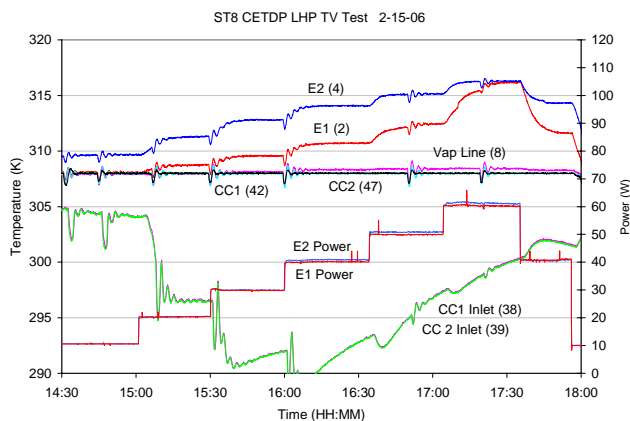


Figure 11. High Power Test

Temperatures of E1/E2 varied with the heat load. At 60W/60W, E1 began to show partial dry-out as indicated by a large increase of its temperature. As the heat load was reduced to 40W/40W, E1 recovered from the partial dry-out.

When a condenser is fully utilized, vapor will exit the condenser and flow into the liquid line. The flow regulator in the current two-condenser MLHP was designed to prevent vapor blow through when one of the condensers was fully utilized as long as the other condenser could still dissipate the total heat load.

Figure 12 depicts the loop temperatures during a flow regulation test. Both CCs were controlled at 293K using TECs and a constant heat load of 30W/10W was applied to E1/E2. Tests were conducted by changing the temperature of one cryopanel while keep the other cryopanel at a constant temperature of 223K. In the first part of the test, the temperature of cryopanel 1 was varied from 223K to 293K and then to 298K. When both cryopanel were at 223K, neither condenser was fully utilized as indicated by the temperatures of both condensers and the liquid exiting the flow regulator. When cryopanel 1 temperature was increased to 293K, condenser 1 dissipated much less heat than condenser 2. Condenser 2 also rose in temperature because its heat load increased. When the cryopanel 1 temperature was increased to 298K, above the CC saturation temperature, condenser 1 could no longer dissipate any heat, and vapor passed the exit of condenser 1. However, the vapor was stopped by the flow regulator, as evidenced by the subcooled temperature of the liquid at the exit of the flow regulator. In the second part of the test, the cryopanel 1 temperature was kept at 223K whereas the cryopanel 2 temperature was varied between 223K and 298K. Similar results were observed. This test demonstrated that the flow regulator performed its function as designed.

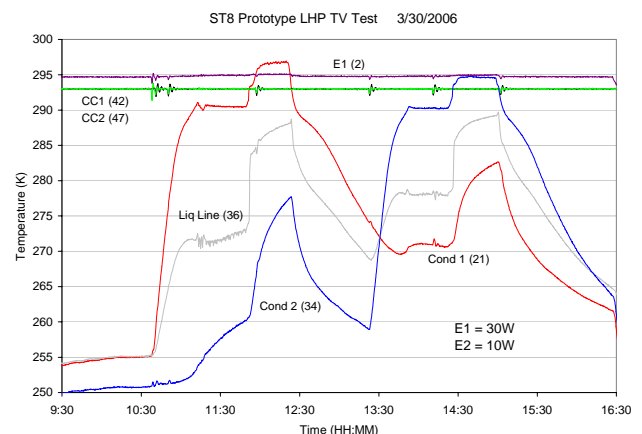


Figure 12. Flow Regulation Test

The heat load sharing test was conducted by changing the following variables one at a time: heat load to the active evaporators that generated the vapor, and the flow rate and temperature of the coolant circulating to the thermal mass of the un-powered evaporator. Figure 13 shows the results of a heat load sharing test. The CC1 temperature was controlled at 303K while the CC2 temperature was not controlled. The two cryopanel were kept at 203K and 243K, respectively. A constant power of 50W was applied to E2, and a constant coolant flow rate of 9.45 gram/sec was maintained for the flow circulating the E2 thermal mass. Initially, the coolant temperature was set at 286K, then increased in steps with increments of 5K. The amount of heat shared by E1 was calculated from the coolant mass flow rate and the difference of the coolant temperature at the inlet and outlet of the E1 thermal mass. As the coolant temperature increased, the amount of heat being shared by E1 decreased because the E1 sink had less heat dissipating capability. Moreover, when the coolant temperature increased to 306K and 311K, the heat being shared became negative, meaning that E1 actually received heat from the coolant and began to work in its normal evaporator mode.

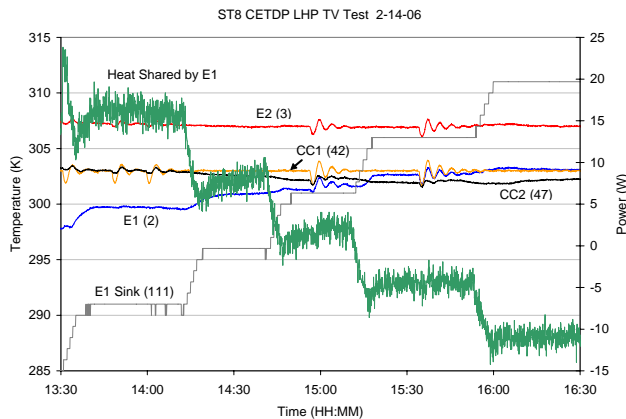


Figure 13. Heat Load Sharing Operation

Tests were conducted to demonstrate the power savings using TECs and coupling blocks as compared to using electrical heaters alone. Figure 14 shows the test results using TEC1 and an electrical heater to control the CC1 temperature at 308K at various E1 heat loads and using 0, 2 and 3 coupling blocks. The results show that TEC could reduce the control heater power by more than 50 percent at all E1 heat loads. The results also show that the coupling blocks were effective in reducing the control heater power whether a TEC or an electrical heater was used. The combination of a TEC and coupling blocks yielded the highest power savings. Furthermore, when a TEC was used, there was no further power savings by increasing the number of coupling blocks from 2 to 3.

In addition to saving the CC control heater power, the TECs had advantages over electrical heaters by providing cooling to the CC and affording the loop to operate below its natural operating temperatures as shown in Figures 7 and 8.

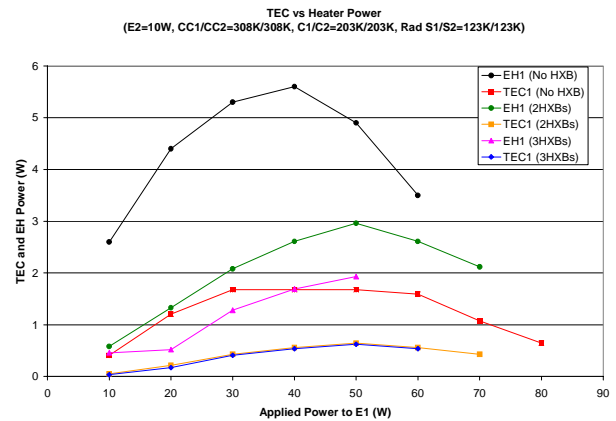


Figure 14. Flow Regulation Test

Table 4 shows the comparison of the TRL 5 validation results and the performance requirements of the Thermal Loop experiment. The TRL 5 validation results verified that the MLHP flight design will meet or exceed the Level 1 requirements.

TRL 6/7 Validation

Figure 15 shows the experiment layout of the Thermal Loop experiment. The MLHP protoflight unit is being built and assembled. The protoflight unit will be tested in a thermal vacuum chamber for TRL 6 validation. The Thermal Loop experiment, consisting of the MLHP protoflight unit and an electronics box, along with the other three experiments, will be integrated into a spacecraft bus built by the Orbital Sciences Corporation, as shown in Figure 16, for TRL 7 validation in space. The target launch date is November 18, 2009. The ST8 has a mission duration of seven months, including one month commission period. The Thermal Loop will be allocated one-month dedicated operational time.

The Thermal Loop flight tests will be divided into several groups; each group is designed to verify a specific operation of the MLHP such as start-up, power cycle, temperature control, heat load sharing, CC set point change, and loop shutdown. Each group can last for several hours to several days. The modular group approach provides flexibility for conducting tests based on the anticipated radiator environment and spacecraft condition (power availability for the time period, accommodations to other experiments, etc.).

Table 4. TRL 5 Validation Results for Flight Design Verification

Test	Requirements	TRL 5 Test Results	Compliance
Start-up	<ul style="list-style-type: none"> An 80% success rate or better on a minimum of 20 start-ups Demonstrate over a temperature range between 273K and 308K 	<ul style="list-style-type: none"> 100% success on 72 start-up tests Temperature range between 258K and 308K 	Exceed requirements
Heat Transport	<ul style="list-style-type: none"> 75W total heat load 	<ul style="list-style-type: none"> 120W total heat load 	Exceed requirements
Operation	<ul style="list-style-type: none"> Control the loop saturation temperature within ± 3K between 273K and 308K Transient operation over full range of heat loads 	<ul style="list-style-type: none"> Control the loop saturation temperature within $\pm 0.5^\circ\text{C}$ between 258K and 308K Transient operation between 5W and 120W with rapid changes of heat load and/or sink temperature Changed saturation temperature between 258K and 308K while in operation 	Exceed requirements
Heat Load Sharing	<ul style="list-style-type: none"> Demonstrate heat load sharing between two evaporators (0W to 75W) 	Heat load sharing was demonstrated by changing 1) heat load to one evaporator (0W to 100W); 2) sink temperature of un-powered evaporator; and 3) CC saturation temperature	Exceed requirements
LHP Model Correlation	Model predictions of LHP critical temperatures within ± 5 K of the test results during steady state and transient operation	Model predictions of the loop critical temperatures (CCs, evaporators, vapor and liquid lines) were within ± 5 K of the test results during steady state and transient operation.	Meet requirement

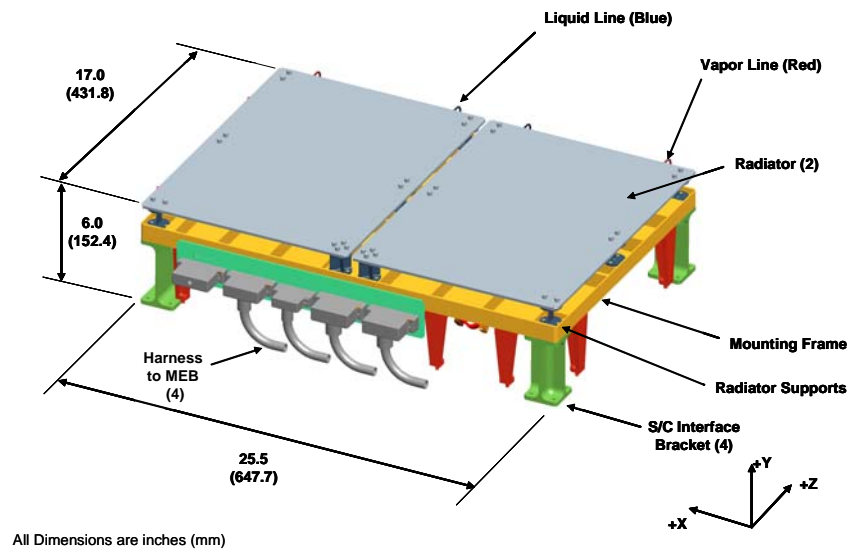
Based on the spacecraft power availability, several modes of flight operation are anticipated: 1) Survival mode when the available power is less than 45 W: Only the survival heaters of the MLHP Assembly and the electronic box will be turned on. 2) Nominal operations mode when the available power is between 45W and 130W. Tests will be conducted for start-up, power cycle, heat load sharing, and operating temperature control. 3) High power operations mode when the available power is between 130W and 190W: the loop capillary limit tests will be performed to investigate the transient behavior of the loop after the capillary limit is exceeded. Test groups will be prioritized so that the Level 1 requirements can be met early in the flight mission. All success criteria can be met in the nominal operations mode.

Conclusion

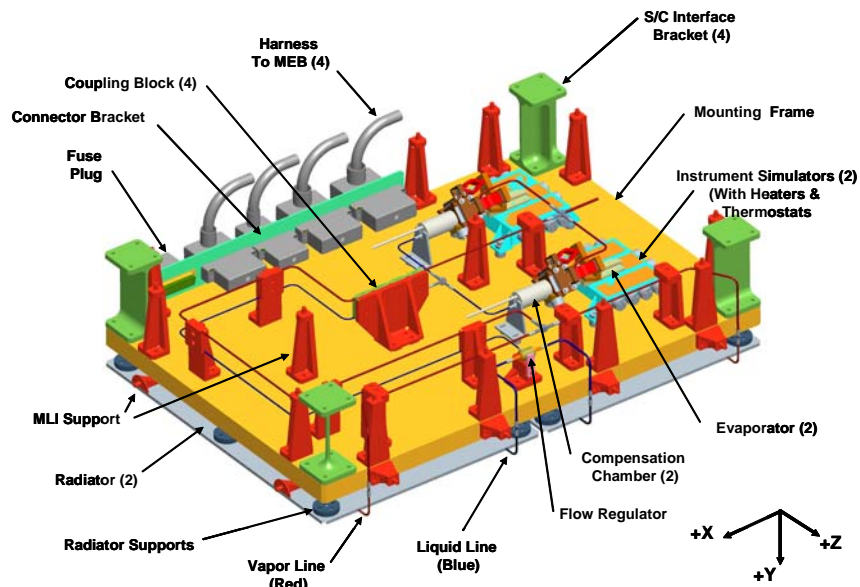
Under NASA's New Millennium Program ST8 project, the Thermal Loop experiment will validate the zero-G performance of an MLHP with two miniature evaporators and two condensers. The MLHP combines the functions of variable conductance heat pipes, thermal switches, thermal diodes, and the state-of-the-art LHPs into a single integrated thermal system. It retains all features of state-of-the-art LHPs and offers additional advantages to enhance the functionality, performance, versatility, and reliability of the system.

An LHP Breadboard has been tested in the laboratory and thermal vacuum environments, and demonstrated excellent performance. An analytical model has also been developed to predict the steady state and transient performance of the MLHP. The analytical model predictions correlated well with LHP Breadboard experimental results. The Thermal Loop technology has attained a TRL 5. A protoflight unit is being built for TRL 6 and 7 validation.

The performance of capillary two-phase devices is known to be strongly influenced by gravity. The large time constant involved in heat transfer requires a long-duration space flight experiment to verify the zero-G performance of the MLHP. Successful flight validation will bring the benefits of MLHP technology to future NASA science missions requiring low mass, low-power and compact spacecraft.



(a) View from Space



(b) View from Spacecraft with MLI Removed

Figure 15. MLHP Flight Experiment Layout

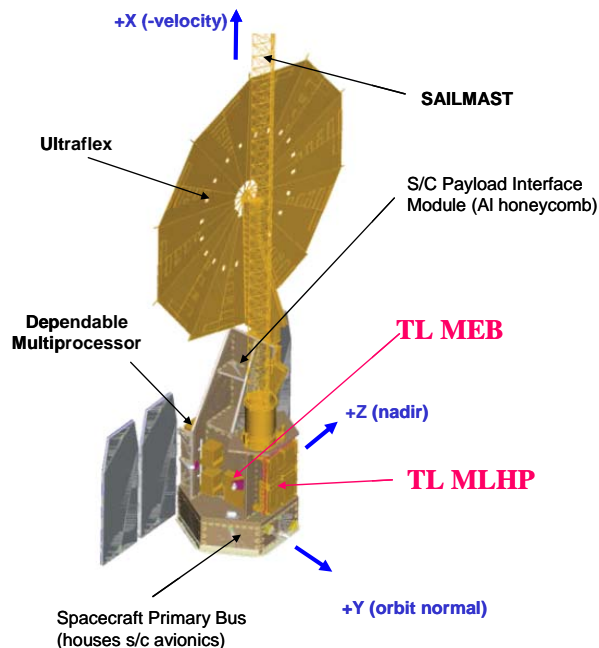


Figure 16. ST8 Spacecraft and Experiment Layout

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